Origins of the Kuroshio and Mindinao Currents

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LONG-TERM GOALS

This study contributes to long-term efforts toward understanding:

- Origins of the Kuroshio Current.
- Circulation of the Western Pacific.

OBJECTIVES

The proposed observational program focuses on understanding:

- Characterize the annual cycle of the Kuroshio and its associated mesoscale variability.
- Quantify Kuroshio spatial structure and temporal evolution.
- Investigate Kuroshio and mesoscale response to strong monsoonal forcing.

APPROACH

The boundary currents off the east coast of the Philippines are of critical importance to the general circulation of the Pacific Ocean. The westward flowing North Equatorial Current (NEC) runs into the Philippine coast and bifurcates into the northward Kuroshio and the southward Mindanao Current (MC) (Figure 1; Nitani, 1972). The partitioning of the flow into the Kuroshio and MC is an important observable. Quantifying these flows and understanding bifurcation dynamics are essential to improving predictions of regional circulation, and to characterizing property transports that ultimately affect Pacific climate. Fluctuations in the Kuroshio and MC can significantly impact variability downstream. For example, the Kuroshio penetrates through Luzon Strait into the South China Sea and

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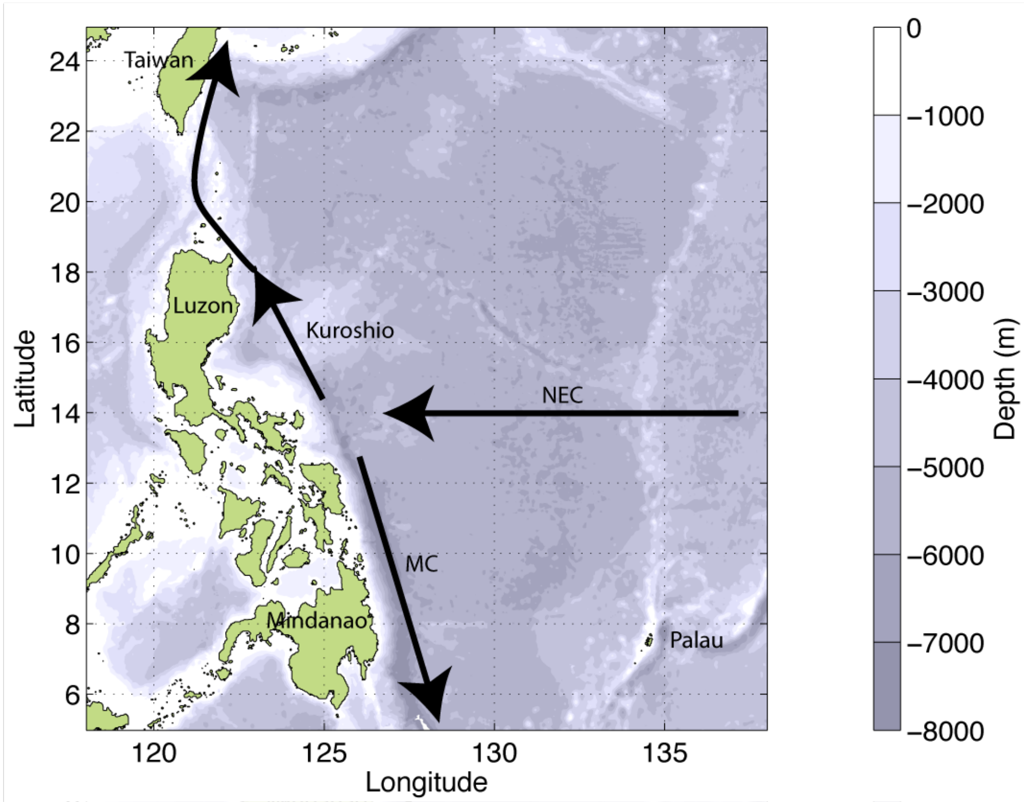

Figure 1. OKMC study region. The major currents of the region are identified: the North Equatorial Current (NEC), the Kuroshio, and the Mindanao Current (MC).

onto the East China Sea shelf. The Kuroshio front dramatically alters stratification and may impact internal wave climate. This effort focuses on quantifying Kuroshio variability and dynamics in the formation region east of Luzon and Taiwan.

Continuous surveys conducted by long-endurance, autonomous Seagliders characterize Kuroshio variability at key points downstream of the NEC bifurcation region. Energetic eddy variability in and near the bifurcation region obscures the Kuroshio, motivating the choice of three cross-Kurohsio sections located at the: (i) southern end of Luzon Strait, (ii) northern end of Luzon Strait and (iii) middle of Taiwan, where the Kuroshio exhibits distinct structure. During the one-year intensive observing period (2012/2013) a fourth glider augments line (i) to focus on the mooring array that spans the Kuroshio at the southern boundary of Luzon Strait. Observations began in June 2011 and will continue through at least December 2013. A combination of Taiwanese research vessels (OR1, OR2, OR3 and OR5; provided by collaborator Professor David Tang, National Taiwan University) and Taiwanese charter vessels (organized by Professor Ming-Huei Chang, National Ocean University) provide support for both routine service and emergency response.

Moored arrays (Lien, Tang and Jayne) complement glider-based sections, extending the measurements into the nearshore zone, where it is energetically inefficient to operate gliders, to provide a complete characterization of the Kuroshio Current. Kuroshio observations will be analyzed in conjunction with simultaneous measurements of the NEC and Mindinao Current to advance understanding of the NEC bifurcation, Kuroshio formation and intrusion into the South China Sea. As in previous projects, glider

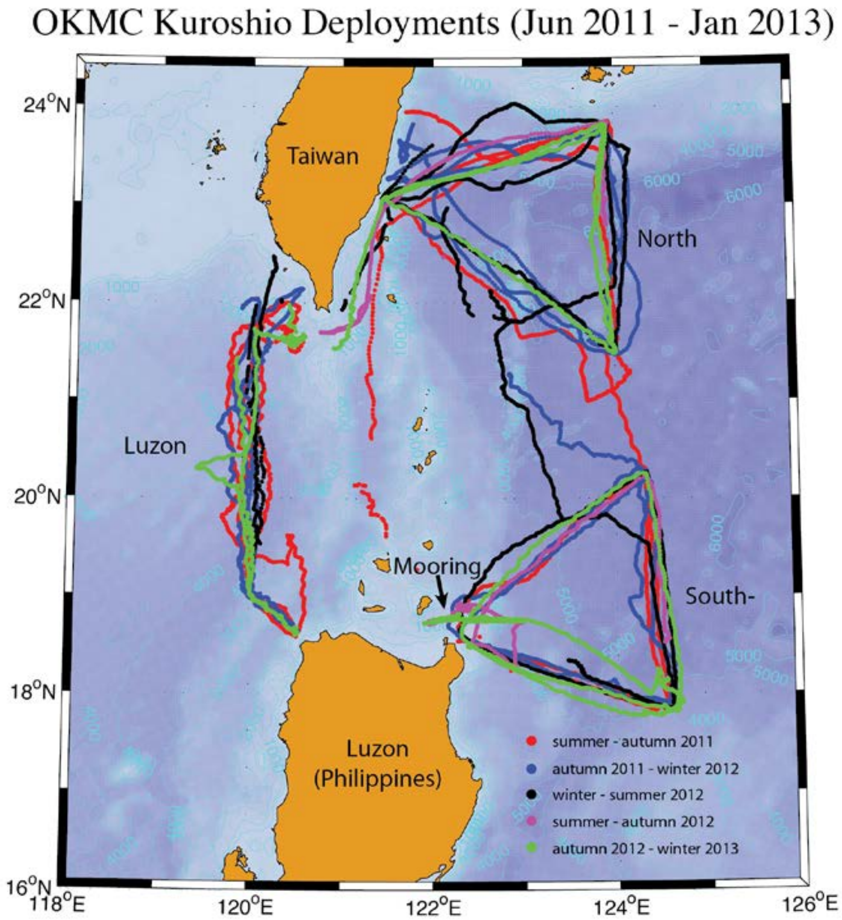

Figure 2. Glider tracks for all OKMC Kuroshio missions as of January 1, 2013. The three continuously occupied patterns ('North', 'South' and 'Luzon') and the line over the mooring array ('Mooring') are marked. Different colors denote the time-progression of the deployments.

data will be made available in real-time to OKMC modeling and assimilation efforts, to operational efforts at the Naval Oceanographic Office and to any other Navy-supported programs that express interest.

WORK COMPLETED

Glider operations began in June 2011, with over 6300 profiles collected as of 4 January, 2013. Surveys span the three base patterns for the entire period, with additional sampling over the mooring array beginning in late summer 2012 and continuing until the moorings are recovered in summer 2013 (Figure 2). OKMC Seaglider missions exploited operational lessons gleaned from earlier Kuroshio deployments (2007-2008) to maintain repeated sampling of a handful of fixed patterns (rather than allowing gliders to be carried downstream), and to better orient sections perpendicular to the dominant current. Experience has also enabled glider sections to extend farther inshore, narrowing the unsampled regions near the coasts. As during previous deployments, operations within the Kuroshio required large buoyancy shifts and high speeds that limited mission duration to roughly four months. Glider surveys provide nearly continuous coverage of the two triangular patterns in the Philippine Sea, north and south of Luzon Strait. The challenges of operating year-round, far from shore aboard small, chartered vessels have complicated deployments and recoveries and resulted in some sampling gaps (Figure 3). Maintaining a persistent, fixed presence in these regions of intense fishing pressure and vessel traffic also involves added risk, which has likely impacted mission success rates.

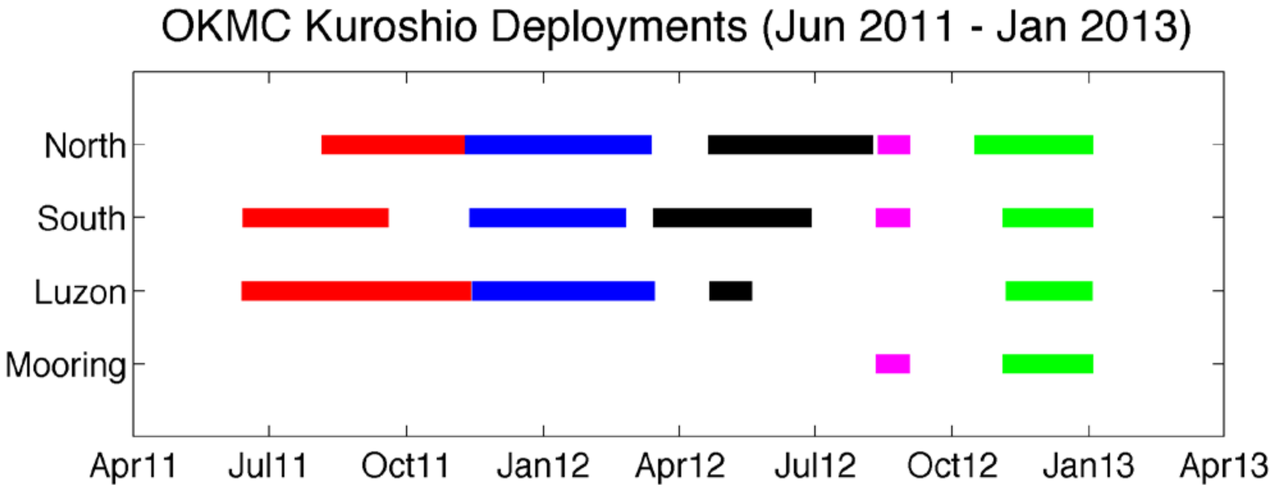

Figure 3. Timing chart depicting temporal coverage of the various surveys patterns indicated on the vertical axis. Colors correspond to the color scheme used in Fig. 1. For example, the red bars in this figure depict the time span of the survey tracks depicted with red markers in Fig. 1. Gliders occupy the 'Mooring' survey only during the period when the moored array is present.

RESULTS

An investigation of diurnal and semidiurnal internal tide provides an excellent illustration of the broad science made accessible by the extraordinary persistence and spatial scope of glider-based measurements provided by the OKMC program, along with the previous Kuroshio, Quantifying, Predicting and Exploiting Uncertainty (QPE), and Impacts of Typhoons on the Ocean in the Pacific (ITOP) programs. Over 18,300 profiles taken between 2007 and the present in the vicinity of Luzon Strait have been used to map the first mode semidiurnal and diurnal internal tide, including coverage just east of the generation ridges and into the Philippine Sea (Figure 4), which had not been well sampled in previous internal-wave focused observational programs. As might be expected given the potential for interactions between internal tide radiating away from generation regions within Luzon Strait and the shear and vorticity fields of the nearby Kuroshio and its associated eddy field, direct relationships between internal tide amplitude and barotropic forcing within Luzon Strait were difficult to identify. Internal tide amplitudes were largest near Luzon Strait (Figure 4, a-d), decreasing to the north and south, with somewhat larger amplitudes west (within the South China Sea) than east (Philippine Sea). More striking was the directly-observed phase progression, both west and east, away from the generation sites within Luzon Strait (Figure 4, e-g). When plotted against longitude (Figure 4, g & h), observed diurnal and semidiurnal internal tide reveal phase speeds consistent with a wave field dominated by mode 1 internal waves radiating east and west from Luzon Strait.

Fitting mode 1 vertical structure to glider observations collected in the upper 1000 m facilitates estimation of the depth-integrated diurnal and semidiurnal energy flux (Figure 5). These estimates provide maps of observed energy flux over a broad regions surrounding Luzon Strait, depicting strong, beam-like westward radiation away from the Strait and somewhat weaker, more variable energy flux fanning out to the east. Observed energy flux patterns resemble those reported from numerical simulations (Niwa and Hibiya, 2004; Chao et al., 2007; Jan et al., 2008; Simmons et al., 2001), with total (depth- and meridionally-integrated) westward and eastward energy flux comparable to that reported from simulations (Niwa and Hibiya, 2004).

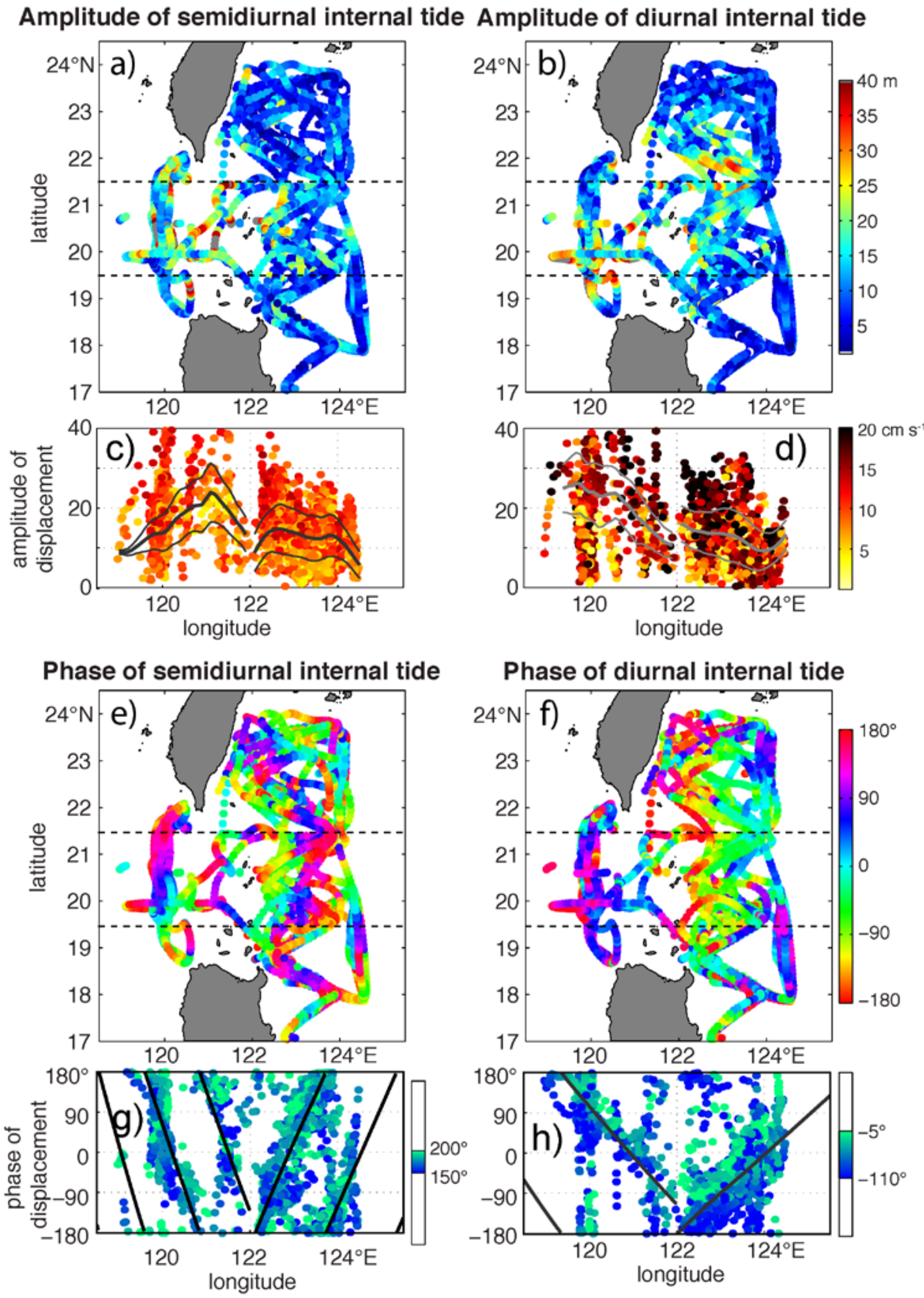

Figure 4. Maps of the (a,b) amplitude and (e,f) phase of the vertical displacement at 500 m associated with the semidiurnal and diurnal internal tide, from all the glider missions. The same (c,d) amplitudes and (g,h) phases at 500 m for all the data in Luzon Strait between 19.5° and 21.5° N (dashed lines in a,b) are plotted as functions of longitude and color-coded by the magnitude of the semidiurnal barotropic currents in (c) and the phase of the semidiurnal barotropic currents in (d). Averaged amplitude as a function of longitude is shown in gray in (c), and gray lines in (d) have a slope equal to the phase speed of a mode-1 wave. Plots of the same quantities for the diurnal internal tide are in panels (e) to (h). Phases are relative to the M_2 and K_1 zonal barotropic currents in Luzon Strait.

IMPACT/APPLICATION

Developed techniques for: (i) using gliders to maintain fixed survey patterns within strong boundary currents and (ii) quantifying internal wave variability using glider-based observations.

TRANSITIONS

None.

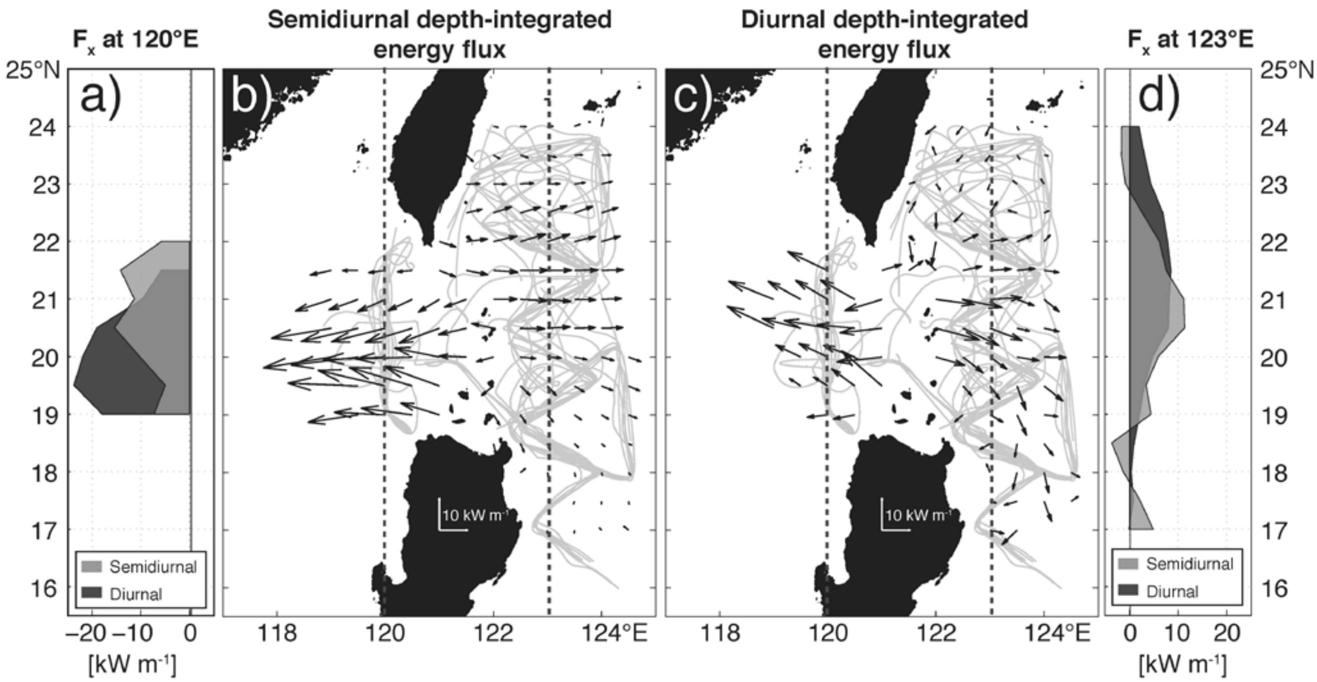

Figure 5. Maps of the (b) semidiurnal and (c) diurnal mode-1 depth-integrated energy estimated from glider data alone. Gray lines mark glider tracks. The zonal energy fluxes along 120° and 123° E are shown in (a, d).

RELATED PROJECTS

Multiple efforts within the Office of Naval Research Origins of the Kuroshio and Mindinao Currents Program. This includes projects directed by principal investigators L. Centurioni, B. Cornuelle, S. Jayne, R-C Lien, J. McLean, B. Qiu, D. Rudnick and T. Sanford.

Glider-based Observations of Kuroshio Seasonal Variability and Loop-Current Intrusion into the South China Sea. C.M. Lee (APL-UW) and D.L. Rudnick (SIO).

An Autonomous Investigation of Kuroshio and Mesoscale Impacts on Upper Ocean Response to Typhoon Forcing. C.M. Lee, J.I. Gobat and L. Rainville (APL-UW).

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